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Microbial Strategies for the Degradation of Organophosphates: A Sustainable Approach to Pollution Control

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ABSTRACT: Organophosphates (OPs) were synthetic chemical compounds that had been applied in household products as well as in agricultural and industrial sectors. Although OPs had proven effective, particularly as pesticide ingredients, their persistence in the environment had raised concerns regarding impacts on ecosystems, the environment, and human health. This study addressed the occurrences and negative impacts of OPs, with a primary focus on microbial degradation as a bioremediation strategy. While various degradation methods had been developed, microbial degradation showed strong potential as a sustainable and cost-effective approach. This review aimed to examine the mechanisms, benefits, and limitations of microbial degradation of OPs, thereby addressing the knowledge gap related to its real-world applications. Microbial degradation involved the use of bacteria capable of breaking down OPs through enzyme production, transforming them into less harmful substances. In comparison with chemical or physical methods, microbial degradation was more environmentally friendly, cost-effective, and adaptable to surrounding conditions. By synthesizing findings from previous studies, the report highlighted both the strengths and shortcomings of microbial degradation in mitigating OPs contamination. The findings underscored its promise as a viable solution, while also pointing to the need for further research and improved frameworks.

KEYWORDS: Organophosphates; microbial degradation; bioremediation; enzymes; environmental impact.

1. Introduction

OPs compounds have emerged as increasing environmental concerns due to their extensive use and persistence. They were produced by the reaction of alcohol and phosphoric acid through esterification. Examples are chlorpyrifos, parathion, phosmet, azinphos-methyl. OPs had

usually been used in pesticides and herbicides, even finding a place as nerve agents in chemical warfare. Their high toxicity had led to contamination of soil, water, and air with serious dangers for the ecosystem, ecological balance, and human health [1, 2]. The synthesis of OPs goes back to 1820 when Jean Louis Lassaigne synthesized triethylphosphate (TEP). The first OPs insecticide introduced into agriculture was parathion developed by Gerhard Schrader in 1944. Since then, OPs pesticides are among the groups of pesticides widely used in agriculture where parathion is the most common. They can be effective in increasing yields of crops, but most often they create an effect on the environment as well. By-products contributed to nitrate leaching and also gave way to soil acidification and loss of fertility of soils.

Because of the risk that is attached to OPs contamination, several degradation methods have been advanced. They include chemical hydrolysis, photochemical breakdown, enzymatic mineralization, oxidation, and dealkylation. Of all these, microbial biodegradation through natural enzymatic pathways within microorganisms has proven among the best environmentally sound approaches since it gives limited harmful by-products compared with the application of chemical treatments [5, 6]. Continuous studies of microbial biodegradation are therefore imperative for minimizing OPs pollution in addition to maximizing ecological safety [7, 8].

This review encapsulates updated knowledge on the sources and occurrences of OPs in the environment and mechanisms of microbial degradation with case studies presented against a background of successful biodegradations. Unlike previous analyses, it tries to synthesize mechanistic insight and applied perspective through an analysis of challenges, advantages, and limitations that exist when applying microbial degradation under real-life conditions. It further articulates major research gaps and possible future directions toward this critical framework in further steps toward actual practice on the ground.

2. Occurrence of Organophosphates

As outlined earlier, OPs have been widely used in agricultural, industrial, and household applications. They were also introduced into the environment through improper waste disposal, raising concerns about their persistence and toxicity.

2.1. Use in agriculture.

In agriculture, OP pesticides have been applied to protect crops from pests, improve yields, and support food security. They were favored for their effectiveness and relatively quicker breakdown compared to older pesticide groups, though their acute toxicity remained a serious hazard. Acute toxicity referred to harmful effects arising from a single or short-term exposure, which made OPs dangerous upon direct contact or inhalation [9]. Agricultural practices have contributed to OPs contamination through runoff and infiltration into soils, rivers, lakes, and groundwater. Their high solubility in water facilitated easy transport across different ecosystems. In Malaysia, for example, OPs pesticides had been commonly used in vegetable plantations and palm oil farming. Farmers who lacked personal protective equipment were often overexposed, leading to pesticide-related poisoning cases. This reflected how OP pesticides, while essential in farming operations, also caused human health risks and environmental pollution when not handled safely [10].

2.2. Use in industry and households.

Beyond agriculture, OPs had also been incorporated into industrial and household products. Industrially, they served as flame retardants, plasticizers, and disinfectants. Organophosphate-based flame retardants (OPFRs) had been introduced as replacements for earlier, more hazardous chemicals. These substances functioned by forming a protective char layer during combustion, yet their physical incorporation into materials meant they could leach into the environment under heat or abrasion. Concerns grew as OPFRs were used extensively worldwide, with potential health impacts increasingly noted. In households, OPs-based insecticides remained in use due to their ability to inhibit the acetylcholinesterase (AChE) enzyme. AChE played a critical role in nerve impulse transmission, and its inhibition caused the accumulation of acetylcholine, leading to respiratory failure, seizures, or even death in severe cases. These effects were not limited to insects but extended to humans, highlighting their dangerous potential. Dust samples collected from homes worldwide revealed the presence of OPs insecticides, underscoring their continued prevalence in domestic environments [11, 12].

3. Distribution of Organophosphates in the Environment

3.1. Presence in soil.

Once OPs were released into the environment, they could be detected across different compartments, including soil. Residues in soil posed risks to both human and animal health. In agricultural settings, soil contamination occurred through direct pesticide application, surface runoff, or the deposition of airborne particles. OPs esters were also observed in soils surrounding industrial facilities, electronic and plastic waste sites, airports, and engineering areas. In some cases, residues had spread several kilometers from their original source, demonstrating their mobility and persistence. The binding of OPs to soil particles was largely influenced by adsorption processes. Soils rich in organic matter or clay retained more pesticide residues than sandy soil due to their finer particles and larger surface areas. This persistence in soils carried the risk of bioaccumulation in plants. Pollutants were taken up primarily through plant roots, where they entered with water and accumulated when uptake exceeded elimination. Such accumulation in crops or fruits created pathways for OPs to enter the food chain, potentially harming humans and animals that consumed contaminated produce [13, 14].

3.2. Presence in water.

Water systems such as rivers, lakes, and groundwater were also vulnerable to OP contamination, mainly through industrial discharge, urban wastewater, and agricultural runoff. Aquatic contamination often originated from the production or application of OP-based pesticides. These compounds were detected not only in surface waters but also in sediments, drinking water, and groundwater. The primary risk from OPs in aquatic environments stemmed from ingestion. Agricultural communities were particularly exposed, as pesticide use near farmlands led to higher concentrations in nearby water sources, especially during rainy seasons. Increased precipitation and runoff transported greater quantities of pesticides into water bodies, raising contamination levels during wet periods. This seasonal variation emphasized the influence of farming practices and rainfall on water quality. Ultimately, contaminated water

sources affected human consumption and other daily uses, reinforcing the environmental and health risks posed by OPs residues in aquatic systems [15, 16].

3.3. Presence in the atmosphere.

Organophosphates were also detected in the atmosphere, though at lower levels compared to soil and water. Airborne contamination typically resulted from spray drift, where pesticide droplets traveled beyond the intended application area. While less persistent in the air since residues were quickly degraded by sunlight, moisture, or deposition onto surfaces, these compounds still posed risks through inhalation, particularly in agricultural communities where spraying was common. Although airborne OPs were considered a minor environmental medium, they acted as a transport pathway, eventually settling into soil or water systems. In this way, atmospheric residues contributed indirectly to wider contamination, linking air exposure with the broader environmental cycle of organophosphates [2, 17].

4. Impacts of Organophosphates

OPs contamination has been detected in aquatic, atmospheric, and terrestrial environments. Their harmful effects stemmed from their toxicity, which influenced human health, ecosystems, and overall environmental balance (Figure 1).

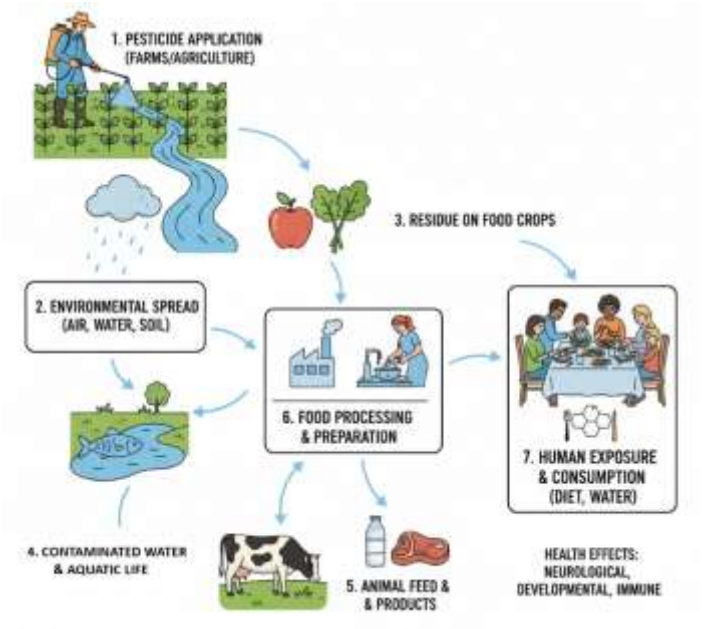

Figure 1. Schematic representation of the environmental pathway OPs contamination and its potential routes of human exposure.

4.1. Human health effects.

One of the most serious consequences of OPs pollution was its impact on human health. Communities were exposed through OP-based products such as insecticides and flame retardants. Application of OPs pesticides often led to residues in nearby soil and water, which were then taken up by crops. This contamination entered the food chain, exposing humans through consumption. Agricultural workers and farming communities were at particularly high risk due to prolonged contact and repeated handling of pesticides. Research demonstrated that OPs acted as neurotoxins, endocrine disruptors, and potential carcinogens. They entered the

body through dermal absorption, inhalation, or ingestion. OPs poisoning was recognized globally as a serious health issue, with millions of cases reported annually. Their neurotoxic effects were linked to the inhibition of acetylcholinesterase (AChE), an enzyme that breaks down the neurotransmitter acetylcholine. When AChE activity was suppressed, acetylcholine accumulated in nerve synapses, overstimulating receptors [12, 18]. This overstimulation caused muscle weakness, respiratory depression, seizures, and in severe cases, death

Beyond neurological effects, OPs also disrupted the human endocrine system. They were identified as endocrine-disrupting chemicals capable of altering reproductive functions in both men and women. In men, exposure was shown to reduce testosterone production, impairing fertility. In women, particularly during pregnancy, exposure was linked to hormonal imbalances in infants, affecting testosterone, estrogen, and other reproductive hormones. Female infants appeared more vulnerable, with reduced levels of key hormones compared to males. These findings demonstrated the severity of OPs exposure, showing how it could damage neurological and endocrine systems with potentially irreversible effects. Preventive measures were therefore essential to reduce the risks associated with ingestion, inhalation, and direct contact [19, 20].

4.2. Environmental pollution.

The widespread use of OPs also resulted in significant environmental pollution, particularly in soil, water bodies, and the atmosphere. In soils, OPs residues accumulated following agricultural applications and waste disposal. Their persistence disrupted microbial communities that played vital roles in nutrient cycling, decomposition, and soil fertility. While some microorganisms declined due to OPs toxicity, others adapted by metabolizing the compounds, leading to imbalances in microbial diversity. Such changes hindered soil health and crop productivity [5, 20]. Furthermore, residues were absorbed by plants, allowing OPs to infiltrate the food chain and increase risks of human exposure (Table 1).

Table 1. Distribution of OPs residues detected in various environmental and biological samples.

Sample Type	Location	OPs Detected	Key Findings	Reference
Vegetables	Changchun, China	Diazinon, Phorate, Dimethoate, Phoxim	Diazinon (82.2%), Phorate (45.8%); 23.4% exceeded MRL	[21]
Water near cocoa farms	Ghana	Chlorpyrifos, Diazinon, Pirimiphos-methyl	Chlorpyrifos: 42.1%, 0.04 ± 0.01 µg/L (< WHO-MRL); others < LOD – max values	[22]
Soil (environmental samples)	Nigeria	Malathion, Methidathion	Malathion: 3.85 ± 6.90 mg/kg; Methidathion: 0.76 ± 3.03 mg/kg; both > MRL	[23]
Water (environmental samples)	Nigeria	Chlorpyrifos	0.05 ± 0.11 mg/L; exceeded WHO MRL	[23]
Made tea, fresh leaves, soil	West Bengal (Dooars, India)	Ethion, Chlorpyrifos	OP residues detected in 100% of samples; chlorpyrifos > MRL in 16–20% of made tea	[24]
Butter	Haryana, India (cotton belt)	Chlorpyrifos (OP)	In butter: 2% samples had OP residues above MRL; specifically chlorpyrifos > MRL in 9%	[25]
Black tea leaves & infusion	Iran	Various OPs among 33 analyzed	86.7% samples above LOD; 40% exceeded European Commission MRLs	[26]
Chili peppers (global data)	Multiple countries (global)	Chlorpyrifos (among top 10)	Chlorpyrifos one of the most frequently detected OPs (~10–29% detection rate)	[27]
Fruits & Vegetables (meta-analysis)	Global	Chlorpyrifos, Profenofos, Dimethoate	~32% of samples contained OP residues exceeding standards; especially chlorpyrifos up to 12× EU limits	[28]

In aquatic systems, OPs contamination primarily occurred through agricultural runoff, leaching, and wastewater discharge. These pesticides negatively affected aquatic microorganisms, disrupted photosynthesis, and reduced biodiversity. Non-target organisms such as fish and invertebrates were especially vulnerable. Contaminated water also posed direct health risks to humans, particularly when used for drinking or irrigation. Seasonal variations, such as heavy rainfall, further intensified OPs concentrations in rivers, lakes, and groundwater [29–31].

In the atmosphere, OPs became pollutants through volatilization and spray drift during agricultural applications. Once airborne, residues spread beyond targeted fields into nearby residential and commercial areas. While OPs were generally less persistent in the air due to breakdown by sunlight and precipitation, they still posed risks through inhalation. Indoor environments, such as workshops or homes containing OPs-based flame retardants, often showed elevated concentrations, further contributing to exposure. OPs had adverse effects on both the environment and human populations. They disrupted biodiversity, degraded soil and water quality, and caused direct harm to humans and animals. Their persistence across multiple environmental compartments highlighted the urgent need for safer management and remediation strategies [32, 33].

4.3. Ecological Effects.

The use of OPs in agriculture and industry had significant consequences for ecological biodiversity. Much like in humans, OPs inhibited the acetylcholinesterase (AChE) enzyme in wildlife, which explained their effectiveness as pesticides. However, this action also harmed non-target organisms, including aquatic animals, birds, and mammals. For instance, fish exposed to OPs-contaminated waters exhibited biochemical changes that reflected tissue damage and stress. Elevated levels of enzymes such as GOT, GPT, ALP, and ACP indicated liver and muscle inflammation, while decreased levels of lactate dehydrogenase (LDH) and triglycerides (TG) suggested disruptions in energy production and storage. These physiological changes highlighted the toxic impacts of OPs on aquatic organisms and their overall health. Mammals also suffered from OPs poisoning, which manifested in muscarinic, nicotinic, and central nervous system (CNS) effects. Muscarinic symptoms included excessive salivation, constricted pupils, and breathing difficulties caused by secretion buildup. Nicotinic symptoms presented as muscle weakness and twitching, while CNS-related impacts ranged from anxiety and depression to seizures. Exposure occurred through multiple pathways, such as inhaling contaminated air, drinking polluted water, or consuming crops treated with OP pesticides. Residues even transferred into animal-derived products like dairy fats, demonstrating how OPs infiltrated food webs [18, 34–36].

5. Mechanism of Microbial Degradation

This study identified that OP contamination was widespread in the environment and posed extreme risks to humans and animals alike. Due to the wide application of OPs in products such as pesticides, herbicides, and flame retardants, their presence was detected in agricultural lands, waste treatment plants, airports, and many other locations. Consequently, developing effective strategies to curb OP pollution was crucial. Several degradation approaches were available, including hydrolysis, oxidation–reduction processes, adsorption, photodegradation, and microbial degradation. Among these, microbial degradation was chosen in this study as the

preferred method for OP residue breakdown. Before biodegradation was considered, practices such as combustion and burial were commonly used, but these approaches often released toxic gases or led to further contamination through leaching into water sources [16, 37].

Microbial degradation referred to the process of breaking down, detoxifying, or converting environmental pollutants using microorganisms and their specialized enzyme systems such as hydrolase, esterase, lactonase, lipase (Figure 2). As xenobiotic compounds, OPs were foreign to natural biological systems; however, certain microorganisms adapted to utilize them as energy and carbon sources. Bacteria such as *Pseudomonas*, *Ralstonia*, and *Rhodococcus* demonstrated strong abilities to degrade xenobiotic compounds. Through evolutionary adaptation, microorganisms developed the capacity to degrade increasingly resistant synthetic chemicals by evolving new genes and enzymatic pathways [38–40].

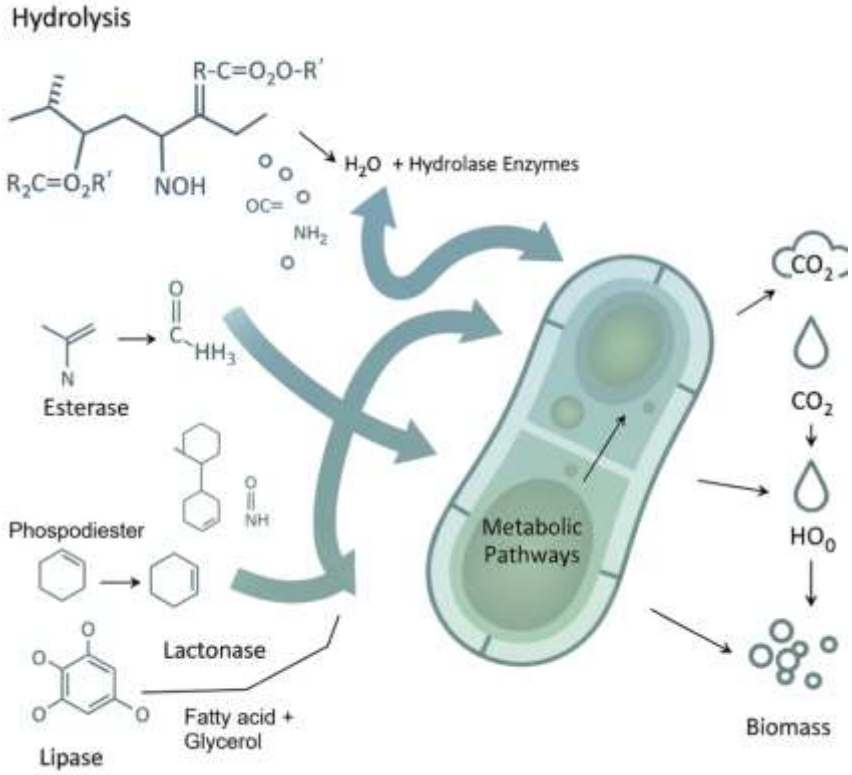

Figure 2. Some mechanism of microbial degradation.

The role of microbial enzymes was particularly significant (Table 2). Different strains produced a wide variety of enzymes capable of breaking down pollutants once considered non-biodegradable. For instance, microorganisms from the *Pseudomonas* family were shown to degrade synthetic plastics such as polyvinyl chloride (PVC), polystyrene, and polyethylene. Although the degradation rate was slow, the process began with microbial colonisation, where bacteria, fungi, and algae formed a biofilm on the plastic surface. Enzymes such as oxygenases initiated bio-deterioration and bio-fragmentation, breaking polymers into oligomers, dimers, and monomers, followed by mineralisation that converted polymer carbon into CO_2. This highlighted the immense potential of microbial systems in tackling synthetic pollutants [7, 41, 42].

Table 2. Enzymes and their catalytic mechanisms involved in the degradation of organophosphate pollutants.

Enzyme Name	Source Organism(s)	Targeted OPs	Reference
Organophosphorus hydrolase (OPH, Phosphotriesterase)	*Pseudomonas diminuta*, *Flavobacterium* sp.	Parathion, Paraoxon, Diazinon, Coumaphos, Chlorpyrifos	[44]
Methyl parathion hydrolase (MPH)	*Pseudomonas* sp. WBC-3	Methyl-parathion, Parathion, Fenitrothion	[45]
Methyl parathion hydrolase (MPH)	*Burkholderia cepacia*	Methyl-parathion, Parathion, Fenitrothion	[46]
Paraoxonase (PON1)	Mammals (such as human serum), engineered bacteria	Paraoxon, Diazinon, Chlorpyrifos	[47]
Phosphodiesterase	*Escherichia coli*, *Klebsiella* sp.	Dichlorvos, Monocrotophos	[48]
Esterase (Carboxylesterase)	*Bacillus subtilis*, *Pseudomonas aeruginosa*	Malathion, Chlorpyrifos, Dimethoate	[49]
Lipase-like hydrolase	*Burkholderia cepacia*, *Pseudomonas* sp.	Triazophos, Chlorpyrifos	[50]
Lactonase (AiiA-type)	*Bacillus* sp., *Agrobacterium* sp.	Chlorpyrifos, Diazinon, Coumaphos	[51]
Phosphotriesterase-like lactonase (PLL)	*Sulfolobus solfataricus*, *Geobacillus* sp.	Paraoxon, Chlorpyrifos, Diazinon	[52]

Similarly, microorganisms also demonstrated the ability to degrade OP compounds. Microbes primarily employed enzymatic hydrolysis, using enzymes such as hydrolases and phosphotriesterases to cleave phosphoester bonds, producing less or non-toxic products. Numerous bacterial species were capable of metabolically or co-metabolically degrading OP pesticides such as chlorpyrifos. In metabolic degradation, the contaminant served as a direct carbon, energy, or nutrient source, often resulting in complete mineralisation. In co-metabolic degradation, the pesticide was broken down incidentally while another compound was metabolized, often leading to partial degradation and the formation of intermediate products such as 3,5,6-trichloro-2-pyridinol (TCP) and diethyl phosphate. The key enzymes responsible for OP degradation were organophosphorus hydrolases (OPH) and phosphotriesterases, both of which acted on the P–O bonds of OP molecules to neutralize their toxicity. The findings of this study emphasized the ability of microorganisms to use OP compounds as growth substrates, highlighting microbial integration as a critical step in bioremediation strategies for cleaning contaminated soil and water [8, 43].

6. Advantages of Microbial Degradation against Organophosphates

6.1. Environmental Sustainability.

There were mainly two degradation strategies for OP compounds, namely abiotic and biotic degradation. Abiotic degradation involved the direct chemical or mechanical breakdown of OPs into simpler, non-toxic forms. For example, chemical methods used oxidants such as ferrate or manganese dioxide, often with catalysts or radiation, to attack the OP pesticide structure. On the other hand, biotic degradation referred to the breakdown of OP compounds by living organisms such as bacteria and fungi through enzymatic activity. Microbial degradation was classified as biotic degradation, as it utilized microorganisms to degrade OP compounds. Microbial degradation was considered a more environmentally sustainable approach since it mainly relied on naturally occurring microbes, reducing the need for synthetic

chemical agents. For instance, chemical adsorption methods required engineered nanostructures, which posed risks of nanoparticle release during production, use, or disposal, potentially worsening environmental and health impacts. In contrast, microbial communities did not require external input to sustain themselves, as bacteria could self-regenerate and maintain their populations under balanced soil nutrient conditions. Hence, microbial degradation proved to be a more sustainable and environmentally friendly method due to its natural self-sufficiency, avoiding the risks of secondary pollution [5, 53].

6.2. Economic feasibility.

Microbial degradation was also regarded as a more cost-effective environmental remediation strategy. This was mainly due to the natural availability and self-regenerating ability of microbes, which eliminated the need for frequent replenishment in contaminated sites. The process required low operational costs because microbial degradation involved minimal intervention. Its mechanism transformed toxic compounds into less harmful forms or achieved complete mineralisation, which aligned with the natural microbial life cycle. Once suitable conditions were established, microbes carried out degradation without requiring extensive human involvement, further reducing costs. Moreover, microbial degradation needed less infrastructure compared to chemical or physical methods, as it could be directly applied to contaminated soil or water without relying on complex treatment facilities [8, 43].

6.3. Adaptive and targeted microbial responses.

Microbial communities demonstrated high adaptability in biodegradation processes. They were able to undergo adaptive evolution, adjusting to environmental changes and developing the capacity to degrade previously resistant compounds. For example, microbes in polluted soils often adapted over time, showing improved efficiency in breaking down persistent pollutants. This adaptability was further enhanced by gene exchange within microbial communities, such as through plasmid transfer, which expanded their degradation potential. In addition to adaptability, microbial systems also offered specificity. Many microbes produced enzymes that selectively targeted specific pollutants, enabling focused degradation without affecting non-target compounds. For instance, some microbial species fed exclusively on hydrocarbons, making them highly effective for degrading spilled oil in marine environments. This specificity gave microbial systems an advantage over chemical methods, which often lacked selectivity and risked causing secondary pollution during application or production [8, 39, 43].

7. Limitations and Challenges of Microbial Degradation of Organophosphates

7.1.Slow degradation rates.

Despite the benefits of microbial degradation, including being environmentally friendly, cost-effective, and adaptive, it also has several drawbacks. One of the primary difficulties is the slow rate of deterioration. While microbes can adapt and degrade pollutants, the process typically necessitates a significant period of time for the microbial communities to adjust to the specific physical and chemical properties of the sites contaminated. The capacity to bioaccumulate is of great importance in determining the efficiency of degradation. When soil particles are contaminated and confined to the soil's micropores, the particles are less likely to be accessed by the microbes, which results in a decrease in the overall rate of degradation.

Residues of organophosphates, in particular, have a tendency to attach to soil in a strong manner, this creates long-lasting bonds that prevent microbial access. As a result, microbial degraders take longer to have an effect on these molecules. Additionally, the activity of microorganisms can be inhibited in environments that are heavily polluted with OPs, this is because toxic concentrations of the chemicals inhibit the growth of cells and the function of enzymes. Despite the fact that microbial degradation effectively diminishes contamination without producing additional chemicals, the process is typically slower than physical or chemical methods and requires additional time to operate [8, 53].

7.2. Dependence on environmental conditions.

The effectiveness of microbial degradation is highly variable depending on the environmental variables, including temperature, pH, oxygen content, and nutrient composition. Variations in these parameters have an effect on both microbial physiology and enzyme activity directly. For example, elevated temperatures typically increase the speed of chemical reactions that are enzymatic, while low temperatures slow the rate of metabolic processes and increase the duration of degradation. Similarly, the environmental pH affects the growth of different microbial species and enzymes, as each species and system of enzymes have an optimal pH range. Other important factors include oxygen availability and the speed and completeness of the aerobic process, this is typically faster and more extensive than the anaerobic pathway, which produces byproducts in the intermediate stage. Also, the availability of nutrients determines the growth of microorganisms and the production of biosurfactants, both of which have the effect of increasing the solubilization and absorption of pollutants. However, in environments with low nutrient content, the activity of microorganisms and the synthesis of enzymes are both significantly reduced. In natural habitats, environmental conditions are often unstable. Seasonal changes, soil diversity, moisture variations, and pollution distribution can influence the performance of microbial species, which can lead to inconsistent results in degradation. Maintaining steady conditions that facilitate microbial activity is considered a significant obstacle in the field of bioremediation [8, 36, 53].

7.3. Microbial survival and genetic stability.

A significant, but often disregarded, restriction in the degradation of microorganisms is the survival and continued presence of microorganisms that are degradeable under environmental stress. In polluted or low-nutrient areas, microbial populations may have a decreased probability of viability due to the toxic effects of pollutants, competition with indigenous microorganisms that do not degrade the plastic, or predation by protists. Additions of exogenous (non-native) degradeurs often lead to poor establishment, this is because these strains have a hard time competing and adapting to their local environment. Similarly significant is the issue of genetic stability. Many of the genes that are important for degradation are located on mobile genetic elements, these elements are lost over the course of several generations without selective pressure from the pollutant. This loss diminishes the long-term stability of the microbial community. Additionally, the horizontal transfer of genes between microbes can change the efficiency of degradation and lead to erratic changes in the performance of microbes. Maintaining the stability, expression, and perpetual expression of genes that are catabolic continues to be a significant obstacle to the consistent performance of biodegradation, particularly in complex environmental systems [53, 54].

7.4.Challenges in scale-up, monitoring, and standardization.

A significant, but often disregarded, restriction in the degradation of microorganisms is the survival and continued presence of microorganisms that are degradeable under environmental stress. In polluted or low-nutrient areas, microbial populations may have a decreased probability of viability due to the toxic effects of pollutants, competition with indigenous microorganisms that do not degrade the plastic, or predation by protists. Additions of exogenous (non-native) degradeurs often lead to poor establishment, this is because these strains have a hard time competing and adapting to their local environment. Similarly significant is the issue of genetic stability. Many of the genes that are important for degradation are located on mobile genetic elements, these elements are lost over the course of several generations without selective pressure from the pollutant. This loss diminishes the long-term stability of the microbial community. Additionally, the horizontal transfer of genes between microbes can change the efficiency of degradation and lead to erratic changes in the performance of microbes. Maintaining the stability, expression, and perpetual expression of genes that are catabolic continues to be a significant obstacle to the consistent performance of biodegradation, particularly in complex environmental systems [54].

8. Conclusion

The extensive use of OPs in agriculture and other sectors resulted in serious environmental and health issues, including contamination of environmental media, disruption of ecological communities, and risks to human health. These impacts highlighted the dangers associated with OPs application. Microbial degradation emerged as an environmentally friendly, cost-effective, and practical strategy to address OPs pollution. Numerous microbial communities, particularly bacteria, demonstrated the ability to transform OP compounds into less harmful substances. Owing to their adaptability, microbial systems represented a strong alternative to conventional chemical remediation methods. Despite these advantages, microbial degradation faced several limitations. The process remained relatively slow and was strongly influenced by environmental factors such as temperature, pH, oxygen, and nutrient availability. Furthermore, challenges related to large-scale application, effective monitoring, and standardisation restricted its implementation in real-world settings. Future progress required more focused research on practical applications, including the improvement of microbial formulations, enhancement of pollutant bioavailability, and development of more reliable monitoring techniques. Overall, microbial degradation of OPs showed great promise, but further efforts were necessary to establish it as a dependable and scalable remediation solution.

Competing Interests

The authors declare that they have no competing interests.

Author Contributions

All authors contributed to the conceptualisation, literature review, and drafting of the manuscript. All authors critically revised the work for important intellectual content and approved the final version of the manuscript.

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Data Availability

No new data were generated or analyzed in this review article.

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